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LOOKING FOR SUPER-EARTHS IN THE HD 189733 SYSTEM: A SEARCH FOR TRANSITS IN *MOST*[1] SPACE-BASED PHOTOMETRY

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ABSTRACT

We have made a comprehensive transit search for exoplanets down to ≃1.5 - 2 Earth radii in the HD 189733 system, based on 21-days of nearly uninterrupted broadband optical photometry obtained with the *MOST* (*Microvariability & Oscillations of STars*) satellite in 2006. We have searched these data for realistic limb-darkened transits from exoplanets other than the known hot Jupiter, HD 189733b, with periods ranging from about 0.4 days to one week. Monte Carlo statistical tests of the data with synthetic transits inserted into the data-set allow us to rule out additional close-in exoplanets with sizes ranging from about 0.15 - 0.31 R_J (Jupiter radii), or 1.7 - 3.5 $R_\oplus$ (Earth radii) on orbits whose planes are near that of HD 189733b. These null results constrain theories that invoke lower-mass hot Super-Earth and hot Neptune planets in orbits similar to HD 189733b due to the inward migration of this hot Jupiter. This work also illustrates the feasibility of discovering smaller transiting planets around chromospherically active stars.

Subject headings: planetary systems – stars: individual: HD 189733 – methods: data analysis – techniques: photometric

1. INTRODUCTION

With the launch of the *MOST* (*Microvariability & Oscillations of STars*) (Walker et al. 2003; Matthews et al. 2004) and COROT (Baglin 2003; Barge et al. 2005) satellites, and the upcoming launch of the Kepler (Borucki et al. 2004; Basri et al. 2005) space mission, the age of transit searches with continuous space-based photometry is now upon us. With these new telescopes we should now be able to utilize the transit method to probe the terrestrial and giant-terrestrial regime of transiting exoplanets. We can seriously anticipate the discovery of a transiting Super-Earth (Valencia et al. 2006) sized planet orbiting a Sun-like star in the near-term future.

Numerical simulations of migrating hot Jupiters have indicated that one might expect Earth, Super-Earth and Neptune sized planets in similar orbits, or in mean-motion resonances with the hot Jupiter (Zhou et al. 2005; Raymond et al. 2006; Mandell et al. 2007; Fogg & Nelson 2007). The interior regions of these hot Jupiter exoplanetary systems, and specifically the mean-motion resonances of these hot Jupiters, have been probed with the transit-timing method in a handful of transiting exoplanetary systems to date - these are TrES-1 (K0 V) (Steffen & Agol 2005), HD 209458 (G0 V) (Agol & Steffen 2007; Miller-Ricci et al. 2007a), and HD 189733 (K0 V) (Winn et al. 2007; Miller-Ricci et al. 2007b; Pont et al. submitted). The transit method, although currently less sensitive in the mean-motion resonances of the hot Jupiter, is able to probe a continuous range of orbital separations in the interior regions of these hot-Jupiter systems. The transit method has only been used to sensitively probe the interior regions of one hot Jupiter exoplanetary system to date; Croll et al. (2007) reported a null-result in the HD 209458 system from the first space-based transit-search using nearly continuous photometry returned by the *MOST* satellite. In that work, Croll et al. (2007) ruled out hot Super-Earth and hot Neptune-sized planets larger than 2-4 Earth radii in the HD 209458 system with periods ranging from 0.5 days to 2 weeks. Here we report a search using *MOST* photometry and similar methods ruling out transiting exoplanets with periods from 0.4 days to one week in the HD 189733 system with orbital inclinations similar to that of the known hot Jupiter exoplanet, HD 189733b.

The existence of a hot Jupiter planet, HD 189733b, in the star system HD 189733 (V = 7.67) was first reported by Bouchy et al. (2005). The planet was detected from radial velocity measurements in the ELODIE metallicity-biased search for transiting hot Jupiters. Photometry of HD 189733 taken by Bouchy et al. (2005) indicated the

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planet HD 189733b transited the star along our line of sight. Follow-up work has determined the stellar and planetary characteristics of the detected hot Jupiter to a high degree of accuracy (Bakos et al. 2006a; Winn et al. 2006; Winn et al. 2007; Baines et al. 2007). A number of researchers have determined characteristics of the planet by measuring the drop in flux during the secondary eclipse. These results include the thermal emission of the planet (Deming et al. 2006), one of the first spectra of an extrasolar planet (Grillmair et al. 2007), as well as the first measurement of the day-night contrast of an extrasolar planet (Knutson et al. 2007). Recent evidence indicates that HD 189733 is likely a binary system with a mid-M dwarf star, HD 189733B (period $\sim$ 3200 yr), as a companion to the main K0 star, HD 189733 (Bakos et al. 2006b). The putative transiting planets that are searched for in our manuscript are assumed to transit the primary star, HD 189733, as does the known planet HD 189733b. Radial-velocity measurements have already ruled out other planets than the known hot Jupiter in this system that are more massive than approximately $\sim$32 $M_\oplus$ (Winn et al. 2006 as quoted in Miller-Ricci et al. 2007b).

Recently, HD 189733 was discovered to display quasiperiodic flux variations at the $\sim$3% level (Winn et al. 2007; Matthews et al. in preparation). This result is in concordance with the results of Wright et al. (2004), which indicated that HD 189733 was a chromospherically active star. Detecting planets via the transit method in chromospherically active stars is a relatively new topic. In addition to the original discovery of HD 189733b around this active star, and the pioneering work of the TEP network (Deeg et al. 1998; Doyle et al. 2000), Hebb et al. (2007) recently found that they could rule-out Jupiter and Neptune-sized planets with short periods via the transit method around the active star AU Mic. We extend these efforts to the Neptune and Super-Earth-sized regime by investigating the continuous and accurate photometry returned by *MOST* to search for Super-Earth and Neptune sized planets with short periods around this active star.

MOST's 21-day observations of HD 189733 are presented in Matthews et al. (in preparation). These observations have already been used to place limits on other hot Super-Earth and hot Neptune exoplanets near the mean-motion resonances of the hot Jupiter in the system through the transit-timing method (Miller-Ricci et al. 2007b). We extend these efforts here by ruling out hot Super-Earth and hot Neptune-sized planets using the transit method. The rotational modulation displayed in *MOST*'s observations of this system has also been fit with a starspot model by Croll et al. (submitted). Their model argues in favour of moderate spin-orbit misalignment between the stellar spin axis and the orbit-normal of the hot Jupiter in this system.

In §2 the *MOST* photometry of HD 189733 is described. The transit search technique is briefly summarized in §3. The Monte Carlo statistics used to estimate the sensitivity of the transit search are specified in §4. The transit search routine is applied to the *MOST* HD 189733 data set in §5, where we are able to rule-out hot Super-Earth and hot-Neptune sized planets in this system. Our results are summarized in §6, including a discussion of the approximate mass of exoplanets that have been ruled out by our results for various compositions of extrasolar planets.

2. *MOST* PHOTOMETRY OF HD 189733

The *MOST* satellite was launched on 30 June 2003 and its initial mission is described by Walker et al. (2003) and Matthews et al. (2004). A 15/17.3-cm Rumak-Maksutov telescope feeds two CCDs, one originally dedicated to tracking and the other to science, through a single, custom, broadband filter (350 – 700 nm). *MOST* was placed in an 820-km altitude circular Sun-synchronous polar orbit with a period of 101.413 minutes. From this vantage point, *MOST* can monitor stars in a continuous viewing zone (covering a declination range $+36^\circ \leq \delta \leq -18^\circ$) within which stars can be monitored without interruption for up to 8 weeks. Photometry of very bright stars ($V \leq 6$) is obtained in Fabry Imaging mode, in which a Fabry microlens projects an extended image of the telescope pupil illuminated by the target starlight to achieve the highest precision (see Matthews et al. 2004). Fainter stars (down to about $V \sim 12$) can be observed in Direct Imaging mode, where defocused images of stars are monitored in Science CCD subrasters (see Rowe et al. 2006a).

MOST observed HD 189733 in Direct Imaging mode for 21 days during 31 July – 21 August 2006. For the first 14 days of this run, HD 189733 was the exclusive target; for the final 7 days, it was shared with another Primary Science Target field during each 101.4-min orbit of the satellite. Consequently, during the last third of the run, HD 189733 was observed only during intervals of high stray Earthshine, resulting in somewhat increased photometric scatter. The duty cycles of the light curve are 94% during the first 14 days and 46% during the last 7 days. Early in 2006 the tracking CCD system of *MOST* failed due to a particle hit. Thereafter both science and tracking were carried out with the Science CCD system. To avoid introducing significant tracking errors exposures were limited to 1.5 sec. 14 consecutive exposures were then stacked on board to improve signal-to-noise, and downloaded from the satellite every 21 sec. Approximately 112,000 of these combined observations were taken.

The photometric reduction was performed by one of us (JFR) using techniques similar to those described by Rowe et al. (2006a) and Rowe et al. (in preparation). The reduction procedure of aperture photometry is similar to that applied to groundbased CCD photometry, but is non-differential. Our reduction pipeline corrects for cosmic ray hits (more frequent during satellite passages through the South Atlantic Anomaly [SAA]), the varying background due to scattered Earthshine modulated at the satellite orbital period, and flatfielding effects. Further details are given by Matthews et al. (in preparation). It should also be noted that HD 189733, and its M-dwarf companion are sufficiently well separated (216 AU or 11.2" [Bakos et al. 2006b]), that they do not contaminate the photometric signal obtained by *MOST*.

2.1. *Additional selection and filtering of the data*

For this transit search, additional selection and filtering of the photometry was done to optimize the data for the application of Monte Carlo statistics. The filtering is an automated part of the transit search routine, and

is thus briefly summarized in §3. This filtering step is described in detail here.

Data obtained during passages through the SAA are conservatively excised from the light curve, due to the increased photometric scatter during those MOST orbital phases, without reducing seriously the phase coverage of the exoplanetary periods searched. The transits of the known giant planet HD 189733b are removed, at the orbital period $P \sim 2.21857$d determined by Bakos et al. (2006a). The first $\sim 0.8d$ of the data-set was excluded from the analysis due to an obvious temperature swing-in effect common to *MOST*. The obvious modulation of the light curve, due to starspot activity, was removed with a cubic spline (Press et al. 1992). The cubic spline was generated with data binned every ~500 minutes; this trend was then subtracted from the unbinned data. This value of ~500 minutes is believed to be optimum, as it effectively balances the competing desires of having a sufficiently short binning time to effectively remove long period modulation, with the desire of having a long binning time to ensure that one is able to recover transits with periods in the upper range of our interesting period range ($P > 5d$). Limited statistical tests have confirmed that this binning value optimizes our sensitivity to transits of HD 189733 with periods in the upper range of our period range. The signal to noise that an individual transit is recovered with can be highly dependent on this binning time for transits of relatively long periods ($P > 5d$). At these longer periods the cubic-spline can filter out much of the amplitude of the transit signal a low percentage of the time. This effect can also be seen with the reduced efficiency at longer periods for the ninety-degree inclination angle case of the Monte Carlo statistics (Figure 3).

MOST suffers from stray Earthshine with its 101.4-min orbital period, and this stray light background can also be modulated at a period of 1 day and its first harmonic (due to the Sun-synchronous nature of the MOST satellite orbit). For this reason, sinusoidal fits with periods within 1% of 1 and 0.5 d were subtracted from the data. After these cuts, any remaining outliers greater than 6σ were excised. In general, there were few points removed by this sigma-cut as few points were such extreme outliers. It is also important to note that the magnitudes of the injected transits (§4) were always at a level much less than this sigma-cut. The data were also median-subtracted, for reasons outlined in Croll et al. (2007). The automatic filtering step removed ~8% of the original data (mostly due to the SAA and stray light corrections).

The HD 189733 light curves before and after these reduction steps are plotted in Figure 1. These filtered data (and the original reduced data) can be downloaded from the *MOST* Public Data Archive at www.astro.ubc.ca/MOST.

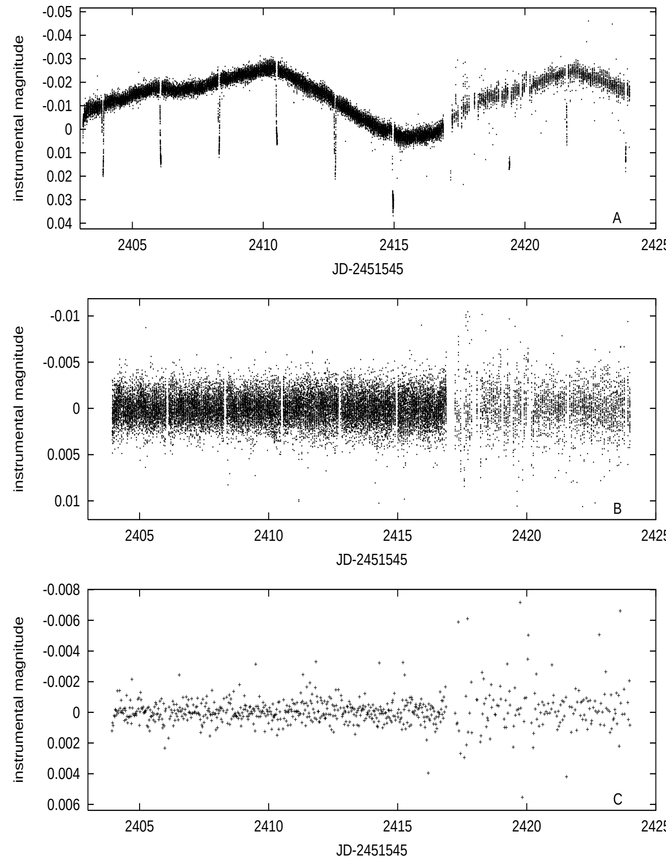

Fig. 1.— The 2006 (A) HD 189733 *MOST* data-set before the automated filtering step. The data following (B) the automatic filtering step, in which the transits of the known planet were removed, and a cubic spline removed the obvious long-term variability. (C) The same data are shown binned in 30 minute intervals at a different vertical scale.

3. TRANSIT SEARCH ALGORITHM

The transit search routine used here is fully described in Croll et al. (2007), and is briefly summarized here. The minor modifications to the routine are highlighted below. The transit routine consists of five steps: (i) an automated filtering step (described in detail in §2.1), (ii) a modified version of the EEBLS (Edge Effect Box-fitting Least Squares) algorithm of Kovács et al. (2002) that searches for box-shaped transits, (iii) selection criteria to select the the best candidates that can be tested for astrophysical plausibility, (iv) realistic transit-fitting and refinement of the transit parameters, and finally (v) detection criteria to differentiate false positives from likely transit candidates.

The detection criteria used in this study are summarized here. We use the transit to anti-transit (the best-fit brightening event with the shape of a transit) ratio statistic (RS) of Burke et al. (2006) to quantify a believable transit. The RS value that a transit has to exceed to be deemed a believable transit is: $\Delta\chi^2\%/\Delta\chi^2_-\% \geq 0.735$, where $\Delta\chi^2$ and $\Delta\chi^2_-$ refer to the normal χ^2 (the sum of sqaured residuals) for the best-fit transit, and anti-transit, respectively. This value was motivated by the results of the Monte Carlo tests (§4). The RS statistic serves to objectively quantify the significance of the measured signal against the correlated scatter in the data, and to thus stringently rule-out false positives. The correlated signal to noise calculation of Pont et al. (2006) serves a similar purpose. The RS will be used in this present application.

The restriction on the quantity f, a measure of the ratio of the strength of any one specific transit compared to the others, as described in Croll et al. (2007), and Burke et al. (2006), was also relaxed such that transits were accepted as long as f < 0.85. This motivation for this less stringent criterion was based on the Monte

Carlo statistics that indicated that a more conservative criterion on f would rule out realistic transits, without an appreciable decrease in the number of false positives in our data-set.

The precise values used for various parameters in the EEBLS step (ii) in the transit search routine are summarized in Table 1. We have decreased the minimum value probed by the EEBLS routine in the application of this transit search routine to HD 189733, compared to its application to HD 209458 in Croll et al. (2007). This is due to the conclusions of Sahu et al. (2006), who observed a number of ultra-short period ($P < 1.0$ d) planet candidates in the SWEEPs survey, and noted that these planets may preferrentially be found around low-mass stars. HD 189733 has a stellar mass of 0.82 $M_{\odot}$ (Bakos et al. 2006a), below the limit of 0.88 $M_{\odot}$ suggested by Sahu et al. (2006) to be indicative of a preference for ulta-short period planets. The minimum period investigated by the EEBLS routine is thus now $0.4d$, a value corresponding to a semi-major axis, a_p, of just under three times the stellar radius ($a_p \approx 2.5R_*$). For comparison, OGLE-TR-56b has a_p≈$4.4R_*$, the smallest orbital radius in terms of its stellar radius of a confirmed planet to date. The maximum period of $6.9d$ is chosen similar to the maximum value for HD 209458 in Croll et al. (2007), as a value that would allow one to observe three distinct transits in the 21 d data-set. This period range of 0.4 to 6.9 d corresponds to 0.01 to 0.07 AU. The minimum fractional transit length is 0.75 times that of the calculated average fractional transit length at that period - a value chosen to ensure the routine remains adequately sensitive to transiting planets with non edge-on inclination angles. We also increase the number of bins, Nb, used by the EEBLS algorithm for short periods compared to the application of Croll et al. (2007) to HD 209458. The number of bins, Nb, used by the EEBLS algorithm for each period, P, is determined by the following formula: $[0.7 \times \exp(-\mathrm{P}) + 1.0] \times 20.0/Qmi$, where Qmi is the minimum fractional transit length to be tested. Qmi, and the maximum fractional transit length, Qma, are determined as given in Table 1, from our average estimate of the fractional transit length for a hypothetical planet, Qm_P, at various periods (Croll et al. 2007).

In our transit selection step we now select the top three EEBLS SR signals, instead of the top two, as well as up to two transit signals with SR signals that are at least 1.8 times the noise floor. A full explanation of these details is provided in Croll et al. (2007). The stellar characteristics used to determine the realistic limb-darkened transit model (iv) are summarized in Table 2. The precise transit parameters are refined using a Marquardt-Levenberg routine (described in detail in Croll et al. 2007). The method used to refine our transit parameters is very similar to the Newton-Raphson method applied by Collier-Cameron et al. (2006) for the same purpose.

4. MONTE CARLO STATISTICS

4.1. *Monte Carlo setup*

To assess the sensitivity of our routine and the *MOST* data-set to smaller transiting planets in the HD 189733 system, simulated transits for planets of various radii and orbital parameters were inserted into the *MOST* photometry and Monte Carlo statistics of the transit recovery rate were generated. We thus proceed under the assumption that all signals in the data-set are noise, and we place as sensitive of limits as possible under this paradigm. Realistic limb-darkened transits due to planets with various radii, R_p, orbital phases, ϕ, periods, P, and inclinations, i, were inserted into the 2006 *MOST* HD 189733 data. The full non-linear model of Mandel & Agol (2002) was used to ensure the inserted transits were as realistic as possible. Circular orbits were used. The M-dwarf companion star, HD 189733B, would have a negligible effect on the orbit of a close-in putative planet in orbit around HD 189733, and thus the effect of this binary companion can be safely ignored.

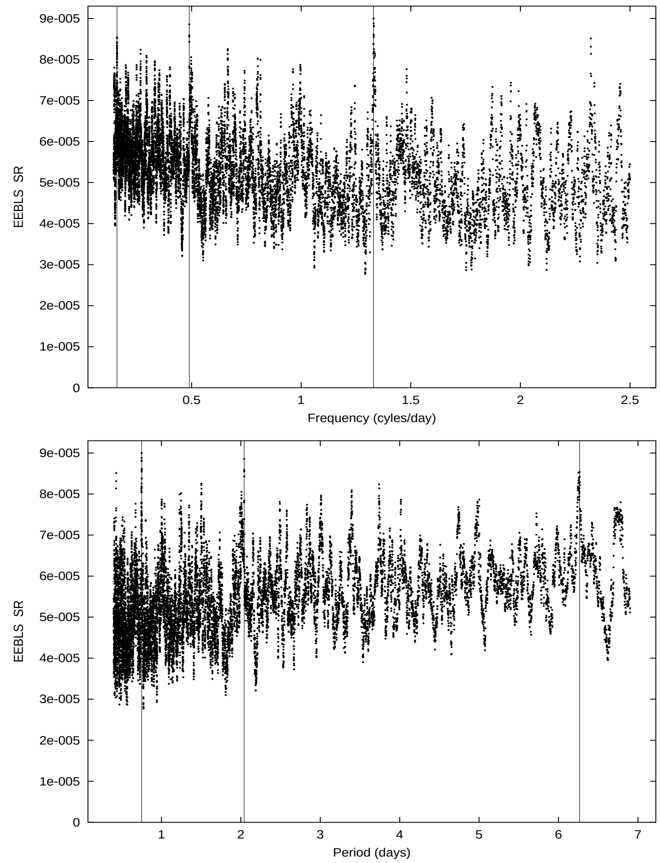

FIG. 2.— The EEBLS spectrum of the *MOST* HD 189733 data-set, plotted in frequency (top), and period (bottom). The 3 candidates that passed the transit selection criteria are shown by the solid vertical lines.

These modified data were then subjected to the transit search algorithm as discussed in §3. It should be noted that this includes the automated filtering step, and thus the synthetic transits were injected before the same filtering process our original data was subjected to, therefore ensuring the validity of the following Monte Carlo limits. Transits were inserted with logarithmic period spacing (as discussed in Croll et al. 2007), with $\eta_{inp} = 0.04$ in the period range $0.45d < P_{inp} < 6.7d$. In total, 36 period steps were used for the 90^o inclination angle cases. For the 86^o and 82^o inclination angle cases transits were inserted with this same logarithmic period spacing until the period exceeded the maximum period, or semi-major axis, that would produce a transit, a $< (R_* + R_P)/\cos i$. For each trial period, simulated transits corresponding to

TABLE 1
EEBLS INPUT PARAMETERS

var	definition	value
Np	Number of Period Points searched	15 000
η	Logarithmic period step	0.000219
P_{min}	Minimum period submitted to EEBLS algorithm	$0.4d$
P_{max}	Maximum period submitted to EEBLS algorithm	$6.9d$
Qmi	Minimum fractional transit length to be tested	$0.75\times Qm_P$
Qma	Maximum fractional transit length to be tested	$1.1\times Qm_P$
Nb	Number of bins in the folded time series at each test period	$(0.7\times\exp(-\mathrm{P})+1.0)\times 20.0/Qmi$

TABLE 2
SYSTEM PARAMETERS

var	definition	value
R_*	Stellar radius	$0.755\ R_\odot$ [a]
M_*	Stellar Mass	$0.82\ M_\odot$ [b]
c_1	Non-linear limb-darkening parameter 1	0.82523168[c]
c_2	Non-linear limb-darkening parameter 2	-0.97755590[c]
c_3	Non-linear limb-darkening parameter 3	1.6867374[c]
c_4	Non-linear limb-darkening parameter 4	-0.65702013[c]

[a] Parameter obtained from Pont et al. (submitted)[b] Parameter obtained from Bakos et al. (2006a)[c] These limb-darkening parameters are fully described in Mandel & Agol (2002) and obtained from Miller-Ricci et al. (2007b).

20 different exoplanet radii were inserted, sampling the period-radius space of interest. For each period and radius at least 100 phases were inserted. For each of these points, the phase ϕ was generated randomly to be in the range $0 \leq \phi < 1$. Because a 2.4 Ghz Pentium processor with 1 Gbyte of memory can perform the transit search algorithm on an individual MOST HD 189733 data set in $\sim$1 minute, exploration of the entire grid just mentioned for all inclinations involves $\simeq 3\times10^5$ iterations and 0.6 CPU years. The calculation was performed on the LeVerrier Beowulf cluster in the Department of Physics and Astronomy at the University of British Columbia using 46 dual-CPU compute nodes.

An inserted transit was judged to be detected if the parameters ϕ and P returned by the transit search algorithm were sufficiently close to the input values: ϕ_{inp} and P_{inp}. The returned period had to satisfy the following criteria: $|P - P_{inp}| < 0.05d$ and $|P/P_{inp} - 1| < 1\%$. The limits of the criterion for ϕ were dependent on the planetary orbital period, because as the period of the putative transiting planet decreases, the fractional transit length increases accordingly. Thus the accuracy required in the determination of ϕ was relaxed for shorter periods. The criterion on ϕ is: $|\phi - \phi_{inp}| < 0.09 - 0.0106 \times (P_{inp}$ - $0.4d)/d$. This corresponds to accepting an error in phase of up to 9% at $0.4d$, but only up to 2% at $7d$. Obvious multiples of the period of the inserted planet, up to 4 times the inserted period, P_{inp}, as well as half-period ($P \approx \frac{1}{2}P_{inp}$), and one-third period ($P \approx \frac{1}{3}P_{inp}$) solutions were also accepted. For the Monte Carlo tests when a transit was deemed recovered the correct period was recovered 96% of the time, while the remainder returned a period that was double, triple, quadruple, one-half, or one-third of the inserted period, P_{inp}.

The level above which a transit recovered from the data-set could be considered believable was also determined due to these Monte Carlo tests, at a level of $\Delta\chi^2\%/\Delta\chi^2_-\% \geq 0.735$ that ruled out 95% of the spurious candidates. Spurious candidates are defined as those candidates where the parameters returned by the transit search routine are different from the parameters inserted for the Monte Carlo tests. The motivation for this criterion is to ensure that a systematic event is misidentified as a believable transiting planet less than 5% of the time. Interestingly we can rigorously rule out these spurious candidates, with our criterion set at a level where the most significant transit candidate can be less significant than the most significant anti-transit (brightening) event. Further discussion on this criterion is given in Croll et al. (2007). So as to not unduly skew this statistic we only generate this statistic using putative planets with radii large enough that the routine has a realistic chance of detecting these planets. We judge this to be planets greater than approximately the 25% contour of our Monte Carlo statistics without the RS criterion. Thus only planets with radii greater than the following limit are used: $R_{Pinp} > (0.10 + \frac{0.05}{6.3} \times (P_{in} - 0.4d)/\mathrm{d})$ R_J.

4.2. *Monte Carlo results*

The fractions of times that the artificially inserted transits were recovered from the data for various radii, periods, and inclination angles are given in Figure 3. Also indicated in Figure 3 is the 68% contour limit that would be placed without the $\Delta\chi^2\%/\Delta\chi^2_-\% \geq 0.735$ criterion. The close agreement between the 68% contour with or without this criterion indicates that this criterion does not seriously impact the sensitivity of the Monte Carlo statistics generated, while providing a robust limit so as to avoid false positives and spurious detections.

We also explore the distribution of spurious signals across period-radii space. These values are displayed in Figure 4, and indicate that spurious signals are negligible (below 1%) other than the intermediate areas where the routine has a small to moderate chance to correctly determine the inserted transit. This result is expected, as it is similar to the result of Croll et al. (2007) for HD 209458.

The performance of our routine is also expected to be slightly degraded at harmonics and subharmonics of the periods that the sinusoids were removed from the data at (P=1.0d, and P=0.5d). Due to the fact that the fractional length of a transit is comparitively large for short periods of 0.5 - 1.0 d, it can be difficult to completely differentiate and properly recover a transit signal near the harmonics and subharmonics of these periods in all

cases. The period ranges demonstrating these drops in survey sensitivity are very narrow ($\frac{\Delta P}{P} \approx 2\%$). Limited statistical tests confirm that the loss in sensitivity near these periods is quite small, similar to that of HD 209458 (Croll et al. 2007).

The harmonics and subharmonics of the orbital period of the known planet HD 189733b, $P \approx 2.218573$d (Bakos et al. 2006a), are also expected to show decreased sensitivity to transits due to the fact that the transits of the known planet were excised from the data. This reduction of sensitivity at these periods is unfortunate considering that it is expected that low-mass planets show a preference for these mean-motion resonant orbits (Thommes 2005; Papaloizou & Szuszkiewicz 2005 and Zhou et al. 2005). The fractional length in phase that was removed at $P \approx 2.218573$ to exclude the transit of the known planet was 4.0% of the total. Thus for the subharmonics of the known planet ($P \approx 4.44d$, $6.66d$) in approximately 4.0% of the cases the routine will be unable to recover a putative transiting planet, as the transits will coincide with the transits of the known planet, and this information will have been completely removed. For the harmonics of the orbital period of HD 189733b, the situation is better, since not all of the transit events would have been removed from the data. For periods near the first harmonic ($P \approx 1.11d$), every second occurance of a transit will be lost in only 8.0% of the cases. For the second harmonic ($P \approx 0.74d$), every third transit would be missed in 12.0% of the cases. For periods near these values the sensitivity limits can be expected to be only slightly degraded from those shown in Figure 3. Even for exact harmonics the routine's sensitivity should be only marginally worse than the limits quoted in Figure 3, as the remaining transits should allow the correct period (or a multiple of the period) to be recovered. The mean-motion resonances from the known exoplanet HD 189733b have been examined using the transit-timing technique with ground-based photometry by Winn et al. (2007), HST photometry by Pont et al. (submitted), and with *MOST* photometry by Miller-Ricci et al. (2007b). It should also be noted that the detection limits presented here are valid for circular orbits, but are largely applicable to orbits of other eccentricities, as summarized for the analogous case of HD 209458 in Croll et al. (2007).

We have made the simplifying assumption that the hypothetical planet that transits the star to produce the synthetic transits of our Monte Carlo statistics does not pass over prominent starspots along our line of sight. The known planet has not been found to occult a prominent starspot in the *MOST* photometry (Miller-Ricci et al. 2007b), although a preliminary investigation of HST photometry of HD 189733 indicates that the planet does occult small to moderate sized starspots during their observations (Pont et al. submitted). Given that the rotational period of the star is greater than the period range that is investigated here, the limits presented here would likely only be slightly adversely affected if this hypothetical planet does pass in front of a prominent starspot. This is because the impact on the transit dip of the planet occulting a large starspot would be relatively short, and should thus not severely affect our limits.

Thus the search routine described above in §3 should be able to detect planets with radii greater than the limits given in Figure 3 with the *MOST* data. In the most optimistic case of an edge-on 90^o inclination angle transit, for planets with periods from approximately half-a-day to one week, this limit is approximately 0.15 to 0.31 R_J, or 1.7 to 3.5 $R_\oplus$, respectively, with 95% confidence. These limits would scale up, or down linearly if the expected stellar radius, $R_* = 0.755\ R_\odot$, is an over- or under-estimate, and are thus perhaps better expressed as $R_p/R_* = 0.020$ and $R_p/R_* = 0.042$ for periods from half-a-day to one week, respectively. For periods at the upper range of those investigated here ($P > 6.5d$) the routine is unable to pick out the transit in a low percentage of cases, because the cubic spline has removed significant power at that period; this effect can be observed as a reduction of sensitivity for longer periods in the ninety-degree inclination angle (i=90^o) panel of Fig. 3. The performance of our automatic routine in this period-radius space probably underestimates the true sensitivity of our survey, as it would be obvious that the cubic spline has overcorrected in these cases through an individual inspection of the phased curve. Also, limited statistical tests have shown that marginally improved limits could probably be set for the shortest periods (P $\leq 3d$) by excluding the last seven days of observations with increased noise, and only producing these limits with the first 14 days of the highest quality data.

5. HD 189733 TRANSIT SEARCH

The *MOST* HD 189733 2006 data-set was submitted to the analysis outlined in §3. There were no transiting planet candidates that met the detection criteria. As the Monte Carlo tests indicate we would be able to detect exoplanets in this system with periods from half-a-day to one week with radii larger than the radius limits given in Figure 3, we can safely rule out these sized-exoplanets in this system.

We also present the details of the candidate with the greatest improvement in χ^2, even though evidence for its existence is marginal. The phased diagram of this candidate (Figure 5) is not particularly convincing, and this candidate did not meet the RS detection criterion, ($\Delta\chi^2\%/\Delta\chi^2_-\% \approx 0.438 \not\gtrsim 0.735$). For these reasons we do not report it as a probable transiting candidate. The specifics of this putative candidate are given in Table 3. This event, with a period of $P \approx 0.752d$, has modest statistical significance, and thus we report it is a possible, but unlikely, candidate. This candidate would correspond to a putative hot Super-Earth, with period P = $0.752d$, radius $R_p = 0.134 R_J$ ($1.50 R_\oplus$), and inclination i = 86.0^o. Interestingly the period of this planet places it quite close to the 1:3 interior mean-motion resonance to the known planet ($P{\sim}0.74d$). For $\rho \approx 3000$ kg m^{-3} the mass of this putative planet would be approximately 1.8 $M_\oplus$ (0.006 M_J). A transit time combined with the supposed period is given in Table 3. Evidence for a transit at this period is marginal, but additional *MOST* photometry of the HD 189733 system should confirm or deny its existence.

The most significant brightening event was one observed with a period of approximately $P \approx 6.28d$. It is likely statistical in nature, and thus is not expected to be related to any specific astrophysical process.

Although our transit search covers a continuous set of periods, we do not expect the existence of another

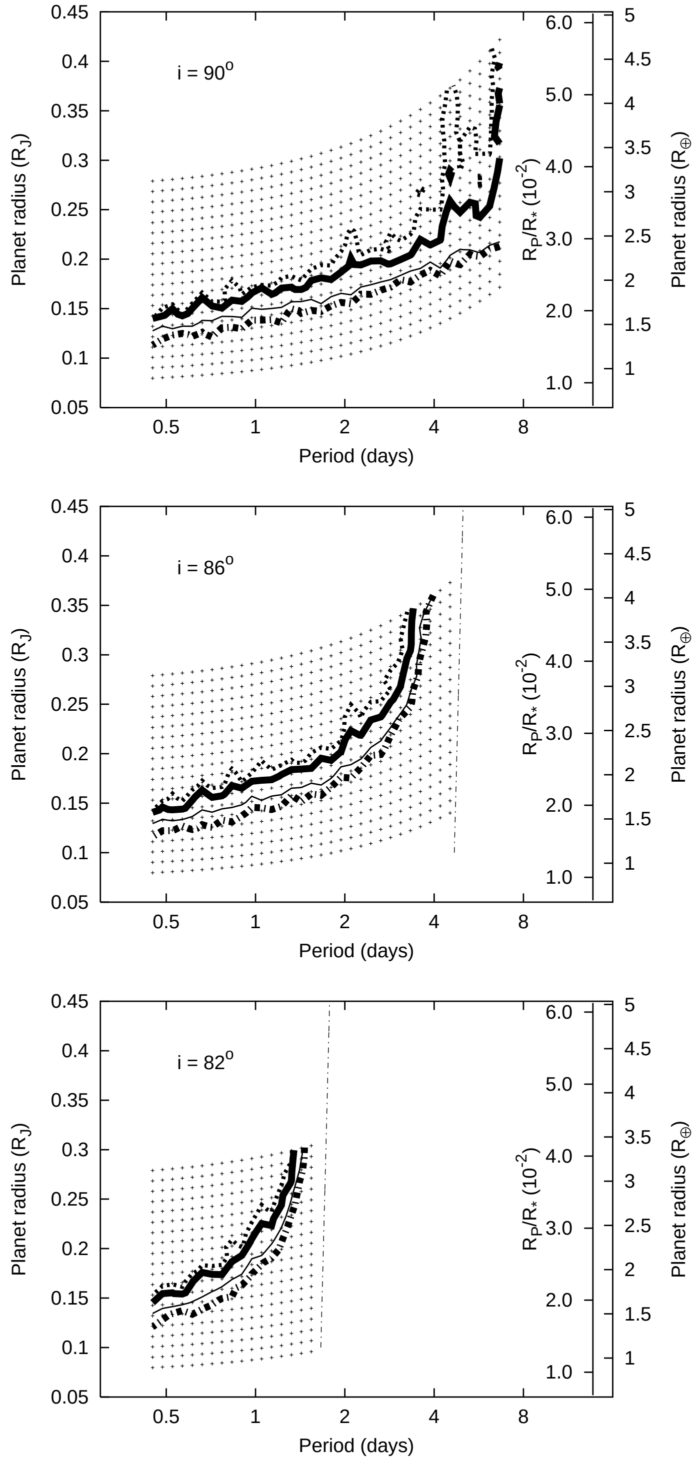

Fig. 3.— Confidence limits of transit detection as a function of planet radius and orbital period, for different orbital inclinations, based on Monte Carlo statistics. The crosses represent the radii and periods at which synthetic transits were inserted in the data. The dotted, thick-solid, and thin-solid lines represent the 99, 95 and 68% confidence contours, respectively. The thick dot-dashed curve represents the 68% confidence contour if the criterion $\Delta\chi^2\%/\Delta\chi^2_-\% \geq 0.735$ was not used. The near vertical dot-dash line in the later panels indicates the maximum period that produces a transit for that given inclination angle. Note the logarithmic period scaling on the x-axis. At least 100 phases were inserted for each of the radii-phase points.

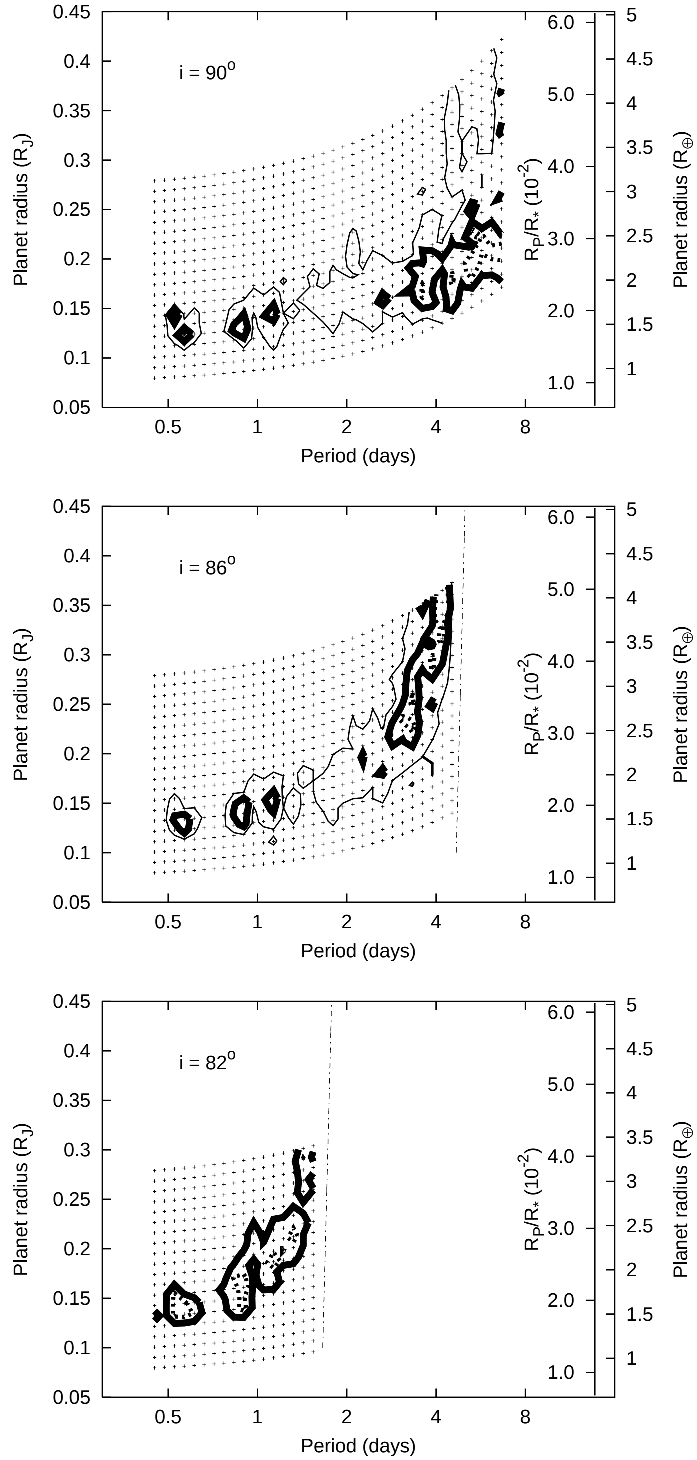

Fig. 4.— The likelihood of spurious transit detections returned by the Monte Carlo statistical analysis. The dotted, thick-solid and thin-solid lines represent the 10, 5 and 1% spurious signal contours, respectively. The format of the figure is otherwise identical to Figure 3. Note that the spurious signals occur in the intermediate regions of the period-radii space of interest, where it is not guaranteed that the correct transit will be recovered, but the inserted transit still causes significant deviations to the light-curve.

planet with a semimajor axis 'too close' to that of the known planet HD189733b, since the gravitational perturbations of the known Jupiter-scale planet will destabilize the orbit of another object. Taking the known planet's data - a_b=0.0313 AU, and mass M_b=1.15 M_{Jup} (Bouchy et al. 2005) in orbit around a star of mass M_*=0.82 solar masses (Bakos et al. 2006a) - orbits in an annulus $a_{in} = (1-\Delta)a_b < a_b < (1+\Delta)a_b = a_{out}$ will be unstable. The fractional width Δ of the annulus is given by (Gladman 1993): $\Delta = 2.40(M_b/M_*)^{1/3}$ where the assumption is being made that the mass of the second planet is much less than the known planet (if not, the width of the zone scales as the cube root of the sum of the masses of the planets). Here Δ=0.26, and so we calculate that planets with periods in the range 1.41 – 3.14 days will be intrinsically unstable due to the presence of the known planet. Thus, some of the parameter space searched in Figure 3 was very unlikely to have been occupied by a second planet - Trojans lagging or leading (Ford & Gaudi 2006) HD 189733b being a notable exception.

We can also exclude transits from planets with longer orbital periods. There were no transits from edge-on ($i = 90^o$) planets with radii greater than $\sim$0.35 R_J (3.9 $R_\oplus$) during *MOST*'s observations of HD 189733, as a planet of this size would be readily visible with even a cursory inspection of the data. A planet of this size would correspond to $\sim$ 20 $M_\oplus$, as calculated from the models of Fortney (2007) assuming a composition similar to Neptune. We can also place a limit on transiting planets with orbital periods from 7 d < P < 10.5 d - in this region we would expect two transits in our data-set. Limited statistical tests indicate that we can rule out planets with radii greater than approximately $\sim$0.32 R_J (3.6 $R_\oplus$) in this region - this corresponds to $\sim$14 $M_\oplus$ (Fortney 2007), again assuming a composition similar to Neptune. We do not provide a formal limit from Monte Carlo estimates for this range of periods as we prefer to restrict our formal transit search to periods that will result in three transits in our data-set.

As an additional sanity check this transit search method was applied to the current data-set without the removal of the transits of the known planet, HD 189733b. As the transits are apparent in the unbinned data (Figure 1), this causes the cubic-spline to over-correct and remove a moderate portion of the signal at this period. Even so, the routine correctly uncovers the transit of HD 189733b with reasonable accuracy. The actual parameters of HD 189733b (Bakos et al. 2006a) were recovered within 0.04% and 0.3% in period and phase, respectively, while the inclination angle and radius were recovered within 1.0^o and $0.20R_J$ of the actual parameters. The moderate discrepancy between the inserted and recovered radius is due to the fact that the cubic spline overcorrects and removes a portion of the transit-signal.

TABLE 3
Transit candidate of marginal significance

parameter	value
P	0.7517d
R_p	$1.50R_\oplus$ ($0.134R_J$)
i	86.0^o
Ephemeris Minimum (JD-2451545)	2403.711
$\Delta\chi^2\%/\Delta\chi^2_-\%$	0.438
Mass (assuming $\rho \approx 3000$ kg m^{-3})	1.8 $M_\oplus$ (0.006 M_J)

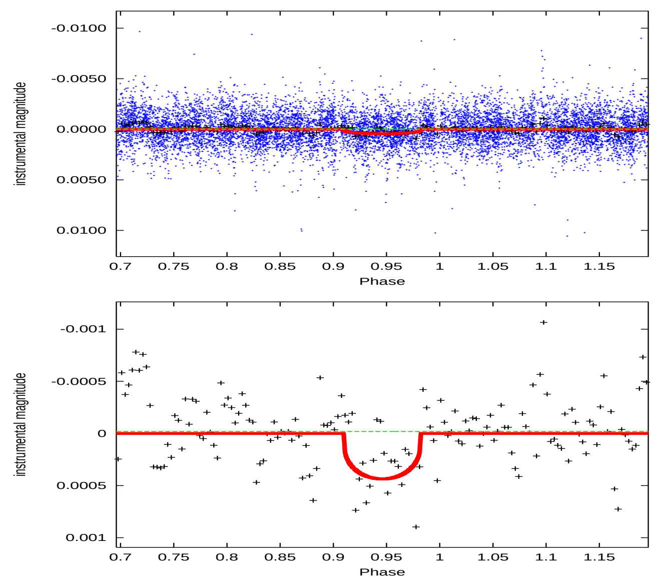

Fig. 5.— The best transit candidate as identified by our analysis of *MOST*'s HD 189733 2006 data-set, but with marginal significance. The thick red-line represents the transit model, while the thin green-dashed line represents the constant brightness model. At top, the unbinned data are shown in blue, and the binned data are shown in black; at bottom the binned data only. As this candidate failed the improvement in transit over anti-transit ratio statistic (RS) criterion, we report it as a possible, but unlikely candidate. The period and radius of this putative planet would be approximately 0.752d and $0.134R_J$ ($1.50R_\oplus$).

6. DISCUSSION

MOST's 2006 observations of HD 189733 have been searched for evidence of other exoplanets in the system. The transit-search routine described in Croll et al. (2007) has been used to search for realistic limb-darkened transits to take advantage of the precise, near-continuous photometry returned by *MOST* and the fact that the stellar characteristics of the star, HD 189733, are well established. Monte Carlo statistics were generated using this routine and indicate that this routine in combination with the aforementioned *MOST* data have placed robust limits in the size of transiting bodies that have been ruled out in this system for a range of periods and inclination angles. In the most optimistic case of edge-on transits, planets with radii greater than 0.15 R_J ($\sim$1.7 $R_\oplus$) to 0.31 R_J ($\sim$3.5 $R_\oplus$) with periods from half-a-day to seven days, respectively, have been ruled out with 95% confidence through this analysis. For orbits co-planar with that of the known planet ($i \approx 86^o$) the limits are similar, except for longer periods (P>4d). For these longer periods the planets cease to transit the star along our line of sight and thus we cannot place firm limits for periods greater than 4-days at $i \sim 86^o$, or for $i < 86^o$. Specifically, we have been able to rule out transiting planets in this system with radii greater than those given in Figure 3. This work has constrained theories that predict hot Super-Earths, and hot Neptunes due to the inward migration of HD 189733b, such as those proposed by Zhou et al. (2005), Raymond et al. (2006), Mandell et al. (2007), and Fogg & Nelson (2007).

It should also be noted that we are able to place very sensitive limits on the size of planets that can be ruled out in this system despite the prominent ∼3% rotational modulation observed in this system. By removing the observed rotational modulation using a cubic spine with a binning time longer than the expected duration of the transit of the planet across the star, we are able to remove the effects of the prominent modulation while remaining sensitive to the transits of planets as small as those expected from hot Super-Earths and hot Neptunes. These methods should be applicable to current or future space-based transit search missions, such as COROT and Kepler.

We are also able to place limits on the size of Trojan planets that have been ruled out in this analysis, assuming the Trojan consistently transits the star with an inclination angle close to that of the known planet ($i \approx 86^o$). We use the definition of Trojans given by Ford & Gaudi (2006) as objects occupying the L4 or L5 stable Lagrange points. Trojans lagging or leading HD 189733b with a radius above $R = 0.24\ R_J$ ($2.7 R_\oplus$) should have been detected with 95% confidence. Using a mean density of $\rho \approx$ 3000 kg m^{-3} this corresponds to 11 $M_\oplus$. A detailed study of this photometry should be able to radically improve this limit on the size of Trojans that can be ruled out with this photometry, assuming the Trojan consistently transits the star along our line of sight.

6.1. *Mass constraints on other Exoplanets in the system*

The above limits on the smallest planetary radii excluded by *MOST* for transiting planets allow some estimates on the type of planets that are being excluded in this system. For Gas Giant planets, including hot Neptunes, radii change with time as the planet cools, so we make use of the fact that the age of the HD 189733 system is greater than 1 Gyr (Melo et al. 2006). We follow the suggestion of Winn et al. (2007) and adopt an age of ∼4.5 Gyr. We thus can refer to cooling models similar to the planets in the Solar System. One exception would be the consideration of possible planets in orbits smaller than that of HD189733b, where tidal heating will lead to larger radii per given mass and composition.

Our radius limit of 1.7 - 3.5 $R_\oplus$ already places us in the realm of Super-Earth and hot Neptune planets. Fortney (2007) has recently provided theoretical predictions for exoplanetary radii for a diverse range of possible exoplanetary compositions, including hot Super-Earth, and hot Neptune planets. The Super-Earth models of Fortney (2007) agree well with the more detailed Super-Earth models of Valencia et al. (2006, 2007). For our Super-Earth exoplanetary limits we use equation 7 and 8 of Fortney (2007). Our inner period limit of $R_P < 1.7 R_\oplus$ allows us to rule out planets more massive than $1.3 M_\oplus$ for a pure ice planet, $4.8 M_\oplus$ for a pure rock planet, and $27 M_\oplus$ for a pure iron planet. Our outer period limit of $R_P < 3.5 R_\oplus$ only allows to place a useful limit on pure ice Super-Earth planets. At this limit we are able to rule out planets more massive than $23 M_\oplus$ for pure ice planets. Pure rock and pure iron planets of this size are moderately less massive, and comparable in mass, respectively, to HD 189733b itself - planets of this mass, of course, have already been ruled out in this system with radial-velocity measurements (Winn et al. 2006 as quoted in Miller-Ricci et al. 2007b). We note that our limit on ice planets may be more sensitive than the limits quoted here as one would expect that ice planets at such small orbital periods would have steam atmospheres, and would thus be significantly inflated at these small orbital seperations (Kuchner 2003; Fortney 2007).

We are also able to place limits on the mass of hot Neptune-type planets that have been ruled out in our analysis. Hot Neptune planets should have cores similar in density to giant ice-planets, and an outer atmosphere of H/He (Fortney 2007) - they should thus be moderately less dense than giant-terrestrial ice planets, and thus be of a similar density to Neptune in our own solar system (Fortney 2007). Our inner period radius limit ($R < 1.7 R_\oplus$) excludes hot Neptunes entirely, as hot Neptune exoplanets are expected to be of similar size to Neptune (3.9 $R_\oplus$) (Fortney 2007; Valencia et al. 2006; Valencia et al. 2007). At our outer period radius limit ($R < 3.5 R_\oplus$) we can rule out hot Neptune exoplanets more massive than 12.2 $M_\oplus$.

The radius limits presented here, combined with the mass-limits from transit-timing analyses (Winn et al. 2007; Miller-Ricci et al. 2007b; Pont et al. submitted), place very firm constraints on the sizes and masses of bodies that could still reside in close orbits to HD 189733. Re-observations of this system planned with *MOST* should be able to further reduce the size of planets that could remain undetected in this system, and further constrain theories that predict hot Super-Earth, and hot Neptune planets in similar orbits to that of the known hot Jupiter exoplanet HD 189733b. HD 189733 thus joins the growing list of hot Jupiter exoplanetary systems (HD 209458 [Croll et al. 2007; Miller-Ricci et al. 2007a; Agol & Steffen 2007], TrES-1 [Steffen & Agol 2005]) for which firm constraints have been placed on the size of other exoplanets in similar orbits to that of the known hot Jupiter by a variety of methods.

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